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Seismic Imaging of Massive Sulfide Deposits: Part III. Borehole Seismic Imaging of Near-Vertical Structures*

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Abstract

Surface seismic profiling is well suited for geologic provinces characterized by low to moderate dip, but it is less effective where dips exceed 65° due to inherent limitations of the recording geometry and processing algorithms. Vertical seismic profiling (VSP), a method used mainly for hydrocarbon exploration in sedimentary basins, overcomes this limitation by utilizing deep boreholes as an alternative acquisition datum. Here, we evaluate the effectiveness of this method for imaging massive sulfide deposits associated with folded and steeply dipping volcanic units near the Kidd Creek orebody in Ontario, Canada. Small (150–225 g) explosive charges placed in a water-filled pit provided a consistent energy source, with sufficient band width and signal penetration to image the target zone to a depth of at least 1.0 km. After preliminary processing, the vertical seismic profile record sections were mapped into cross sectional format using a transformation based on ray tracing. This transformation facilitates the extrapolation of subsurface contacts updip from borehole intersections, and the resulting images delineate several stratigraphic contacts in addition to a prominent seismic reflection from a massive sulfide body.

Introduction

SEISMIC reflection profiling, the main geophysical exploration technique for hydrocarbon exploration in sedimentary basins, has not been used extensively to date for mineral exploration. Recent studies, however, point to the potential utility of seismic methods for the detection and delineation of massive sulfide deposits in crystalline host rocks. Laboratory measurements (Salisbury et al., 1996) show that acoustic impedance (the product of compressional wave velocity and density) for most massive sulfides is significantly greater than acoustic impedance for typical silicate host lithologies. Thus, massive sulfide orebodies are expected to produce prominent seismic reflections. Surface seismic profiling in an area of moderate dip (Milkereit et al., 1996) confirms that massive sulfides (as well as other geologic contacts where rocks with contrasting acoustic impedance are juxtaposed) can be highly reflective.

Geologic settings characterized by steep dips (>65°) are problematic for surface seismic methods, however. When a seismic reflector is steeply dipping, difficulties arise because a large fraction of the reflected energy may be directed horizontally or even downward (Fig. 1). Consequently, in order to record reflections from deep target zones the receiver array may need to extend an impractically large distance away from the seismic source. In cases where seismic velocities increase rapidly with depth, recently developed turning-ray methods (Hale et al., 1992) offer a possible solution to this problem; in practice, however, application of these techniques is limited to young sedimentary basins. A different approach is therefore needed to resolve steeply dipping structures in a crystalline-rock environment.

Vertical seismic profiling provides a logical alternative to surface seismics for this type of setting. In a vertical seismic profile survey, receivers are situated in a borehole in order to record the subsurface wave field generated by surface sources. This configuration is generally better suited than surface recording for intercepting horizontally propagating reflections generated by a steep contact (Fig. 1). In this paper, we present vertical seismic profile data from the Canadian Shield in the vicinity of the Kidd Creek massive sulfide deposit, located in the Abitibi subprovince of the Superior province. The survey was designed to image structures and potential massive sulfide deposits hosted by a folded and steeply

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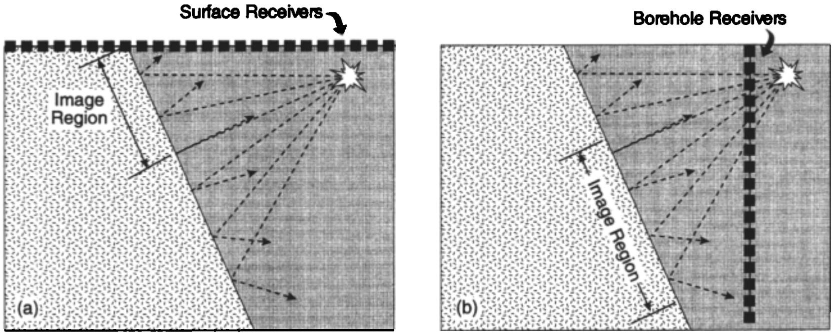

FIG. 1. (a). Schematic ray paths (dashed lines) for a seismic reflection from a steeply dipping geologic contact. Receivers at the surface are represented by solid squares. For this acquisition scenario, the image region is confined to the shallow portion of the reflector, since rays that reflect at deeper locations are directed away from the receiver array. (b). Same as (a), showing the image region for reflected rays that are recorded by borehole receivers.

dipping felsic volcaniclastic unit, referred to as the North Rhyolite. The North Rhyolite study area was selected, rather than the Kidd Creek deposit itself, because acoustical scattering from large mined-out cavities would most likely have overwhelmed the seismic response of the intact part of the Kidd Creek massive sulfide deposit.

After reviewing data acquisition and processing procedures, we illustrate how vertical seismic profile techniques can be used to obtain cross sectional images of steeply dipping panels of contrasting rock types. By correlating reflections from the vertical seismic profile survey with a second borehole where geophysical logs are available, we demonstrate that a known massive sulfide lens produces a prominent reflection and so is detectable using this approach.

Geologic Setting

The present study was conducted in the Abitibi subprovince near the giant Kidd Creek Cu-Zn massive sulfide deposit (Fig. 2). In this area, the Archean volcanic stratigraphy consists of thick packages of basaltic and ultramafic flows, related subvolcanic sills, and intercalations of texturally diverse felsic units. The giant Kidd Creek orebody is spatially associated with one of the felsic extrusive centers and was formed by an exceptionally long-lived hydrothermal event (Walker et al., 1975; Bleeker, 1995; Bleeker and Parrish, 1996). The orebody and its hosting felsic stratigraphy are now situated in the deformed and overturned western limb of a steeply plunging F_1 antiform (Bleeker, 1995). All rocks are affected by regional greenschist facies metamorphism.

In the vicinity of the Kidd Creek mine, several other felsic units (rhyolites) with a potential to host economic ore deposits are known to occur. One of these felsic units, the North Rhyolite, comprises a tabular subvertical package of felsic volcanic rocks that strikes roughly northwest for 1.5 km north of the mine (Fig. 2). It is this North Rhyolite felsic unit that forms the focus of the vertical seismic profile experiment. This relatively thin felsic unit (averaging approximately 30 m in thickness) dips steeply toward the northeast to a vertical depth of at least 1.5 km. It is flanked by serpentinized ultramafic rocks and gabbro to the southwest and by basaltic flows to the northeast. In the discussion below, the contact between basaltic flows and the North Rhyolite unit is referred to simply as the North Rhyolite contact. Similarly, the contact between serpentinized ultramafic rocks and gabbro is referred to as the gabbro contact. The intervening stratigraphy, including the North Rhyolite, is herein referred to collectively as the North Rhyolite volcanic complex.

Massive pyrite-rich sulfide lenses enveloped within carbonaceous sedimentary rocks occur locally at the stratigraphic top of the North Rhyolite or are intercalated within the felsic volcanic package. The long axes of these strata-bound, flattened sulfidic lenses are oriented downdip. Detailed laboratory velocity and density measurements obtained on samples from the Kidd Creek camp (Salisbury et al., 1996) indicate that these sulfides are characterized by anomalously high acoustic impedance values relative to the felsic host lithology. This strong contrast in acoustic impedance implies that sulfide lenses of sufficient thickness and of sufficient lateral extent (see discussion in Salisbury et al., 1996) should be detectable. This premise provides the fundamental basis for the application of seismic methods to mineral exploration in this area.

Vertical Seismic Profiling

Although vertical seismic profiling is a well-established technique for hydrocarbon exploration (e.g., Dillon and Thomson, 1984; Hardage, 1985; Köhler and Koenig, 1986), few such surveys outside of sedimentary basins have been reported in the literature. Examples of nonhydrocarbon vertical seismic profile experiments include several studies associated with continental scientific drilling programs, such as the Cajon Pass drill hole in the southwestern United States (Rector, 1988) and the KTB drill hole in southern Germany (Luschen et al., 1991). In a more recent study, Miao et al. (1995) analyzed vertical seismic profile data near Sudbury, Canada, and used their results to establish a stratigraphic tie with a coincident surface seismic profile. However, in that study the geologic dips are shallow (~10°), in contrast with the steep dips (~70°) that characterize the present study area.

Several source configurations are common for vertical seismic profile acquisition. Zero-offset surveys, in which the source is situated at the borehole collar, are typically used to calibrate surface profiles by permitting precise identification

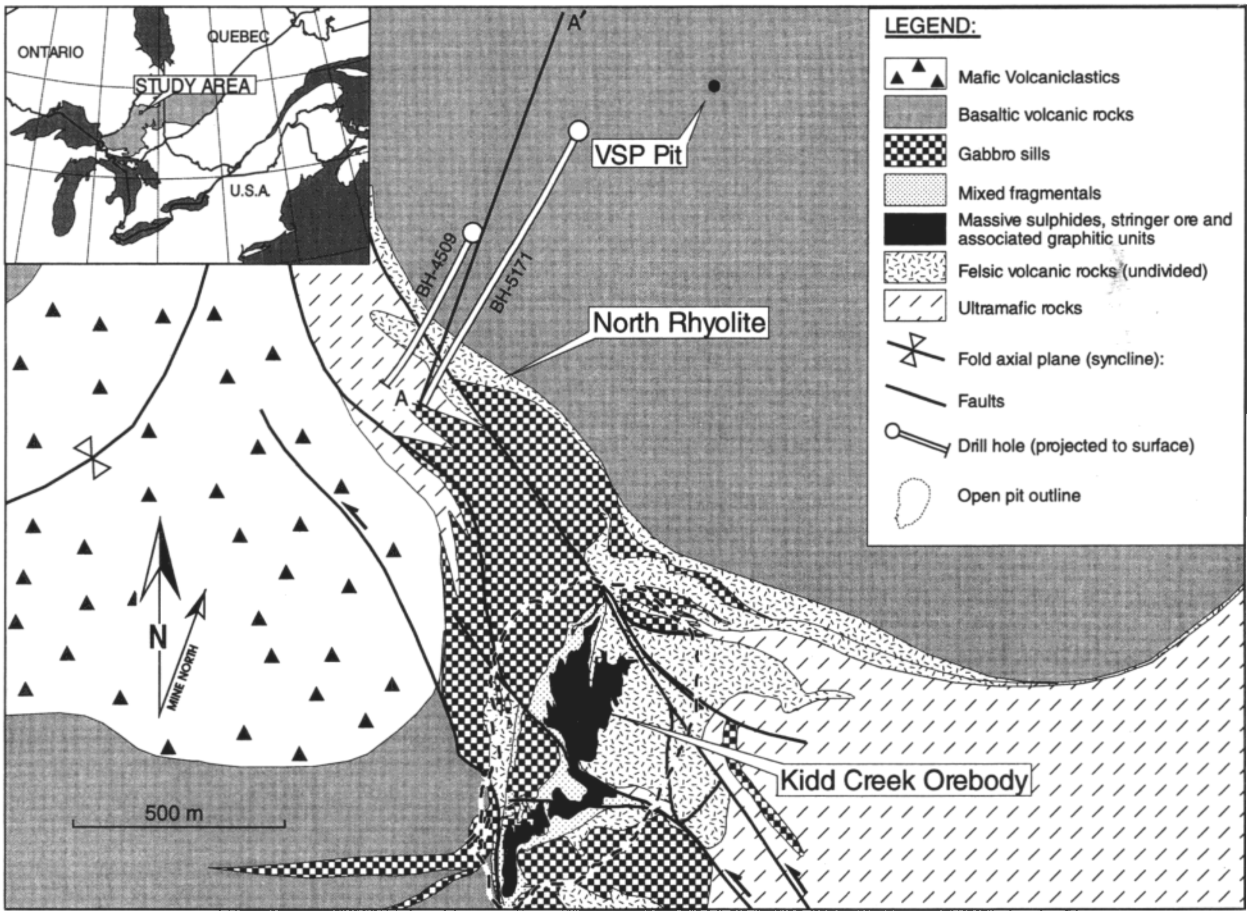

FIG. 2. Geologic setting of the giant Kidd Creek Cu-Zn deposit and the North Rhyolite trend, showing location of the vertical seismic profile borehole (BH-5171), the logging borehole (BH-4509), and the vertical seismic profile source pit. Inset shows location of the study area within the Abitibi subprovince (lightly shaded area).

of subsurface reflectors and determination of interval velocities. By spatially separating the source from the borehole, as in the case of the vertical seismic profile survey described here, reflective stratigraphic and structural contacts can be extrapolated away from the borehole into the surrounding rockmass. In addition, certain types of coherent noise (e.g., tube waves) are reduced when the source is offset from the collar.

Survey Design and Acquisition

The vertical seismic profile data were acquired in a highly deviated borehole (BH-5171) during February 1994, together with another three surveys (not discussed here) that used other combinations of receiver boreholes and/or source locations. The NQ (6.03 cm) diameter diamond drill hole required specialized equipment, since most vertical seismic profile acquisition systems are designed for larger diameter holes. The downhole tool, or sonde, consisted of three 14-Hz geophones in a sealed probe, with a side arm for clamping the unit to the borehole wall. To obtain measurements of the full particle-motion vector, the geophones were oriented with one mounted longitudinally (V in Fig. 3) and two mutually perpendicular geophones that remained orthogonal to the borehole axis (H_1 and H_2 in Fig. 3). The sonde was connected

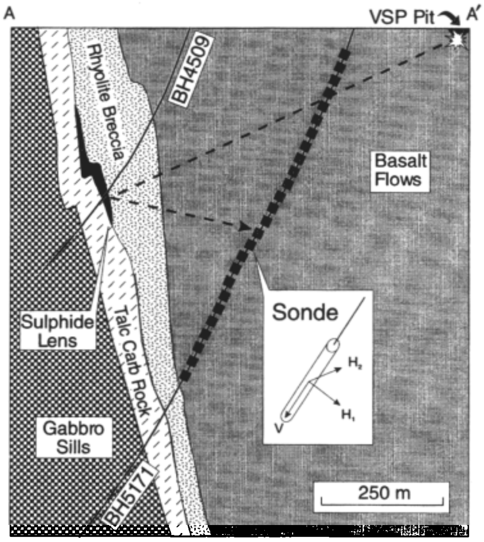

FIG. 3. Simplified geologic cross section along profile A-A' (Fig. 2). The receiver array, represented by the line of solid squares, occupies part of BH-5171 between 106 and 1,030 m. Inset shows the orientation of the three geophones, parallel (V component) and perpendicular (H_1 and H_2 components) to the borehole. Dashed line shows an example reflection ray path.

using a seven-conductor cable to a Bison 12-channel recording system located at the borehole collar.

The seismic source was located about 400 m northwest of the borehole collar and consisted of a pentolite booster (both 150-g and 225-g charge sizes were used) inserted at the bottom of a small pit excavated into surficial clays. During acquisition, the vertical seismic profile pit was filled with water to a minimum depth of 3 m. This system provided a consistent source signal with adequate energy penetration for the depths of interest. Recording levels extended to 1,030 m (wireline depth), the approximate depth level of the North Rhyolite contact, with receiver levels every 15 m in the borehole.

Seismic modeling conducted prior to acquiring the data showed that the image region for the vertical seismic profile survey is confined to the volume of rock to the southwest of BH-5171, above the borehole receiver array. Additional subsurface control in this image region is provided by a second borehole, BH-4509, which intersects many of the same stratigraphic contacts as BH-5171 in addition to a 14-m-thick interval of semimassive to massive sulfides. Wireline velocity and density logs were also available in BH-4509, but not BH-5171.

Data Processing

The generalized steps used to process the vertical seismic profile data can be summarized as follows: (1) suppression of noise, such as 60-Hz interference and direct arrivals, in order to bring out weaker reflected signals, (2) rotation of the data components oriented orthogonal to the borehole into a shot-oriented frame of reference, and (3) enhancement of the reflected arrivals by coherency filtering. The second step is required because the sonde rotates around the axis of the borehole when it is unclamped between receiver levels. Prior to rotation, the absolute orientations of the H_1 and H_2 receiver components are unknown and a statistical analysis of the direct P-wave arrival is used to determine the required angle. The two new data components produced by rotation of the H_1 and H_2 receiver components are referred to as radial (pointed toward the shot) and transverse. A final processing step, that of positioning reflections at their approximate place of origin in the subsurface, is discussed in the interpretation section below.

The survey was conducted in an active mining environment, and the raw recorded data are contaminated by significant interference from 60-Hz noise from a variety of sources. Figure 4a shows the data after filtering to remove 60-Hz and associated harmonics. The most conspicuous arrivals are direct waves, propagating away from the shot, which tend to have much larger amplitudes than the reflections from subsurface structures of interest. The procedure for removal of the direct arrivals (e.g., Hardage, 1985) consists of aligning traces according to first-arrival time picks, application of a 13-point median filter, subtraction of the median-filtered traces from the unfiltered traces, and restoration of the aligned residual traces to their original start times.

The vertical seismic profile data are shown in Figure 4b, after successive removal of both the P-wave and S-wave direct arrivals by this technique. Numerous upgoing reflections are now apparent that have the opposite sense of dip with respect to the direct arrivals. In cases where these reflections can be followed to their point of intersection with the P-wave direct arrival, it is possible to determine unambiguously the stratigraphic level where the reflection originated. For example, a prominent upgoing arrival (R, Fig. 4b) originates at the North Rhyolite contact. Reflections that arrive immediately after R are constrained to be from the underlying stratigraphy, and therefore, most likely originate within the North Rhyolite volcanic complex.

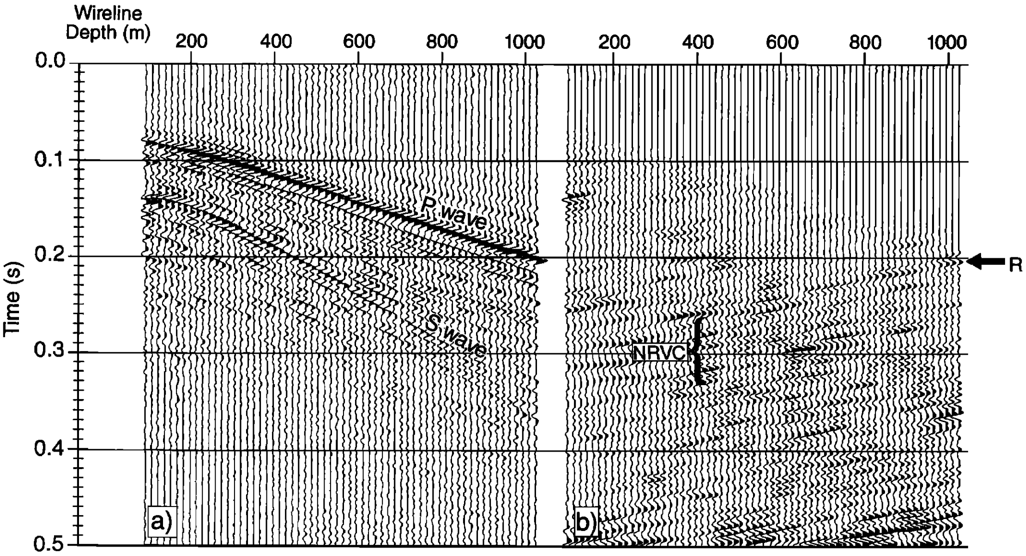

FIG. 4. (a). Vertical seismic profile data after rotation into radial (i.e., orthogonal to the borehole, pointed in the direction of the shot) orientation and application of a filter to remove 60-Hz noise. The most prominent events are the downgoing P-wave and S-wave arrivals. (b). Radial component vertical seismic profile data from (a) after processing to remove downgoing waves and enhance reflected arrivals. The reflection from the North Rhyolite contact (R) is now visible, as well as underlying reflections associated with the North Rhyolite volcanic complex (NRVC).

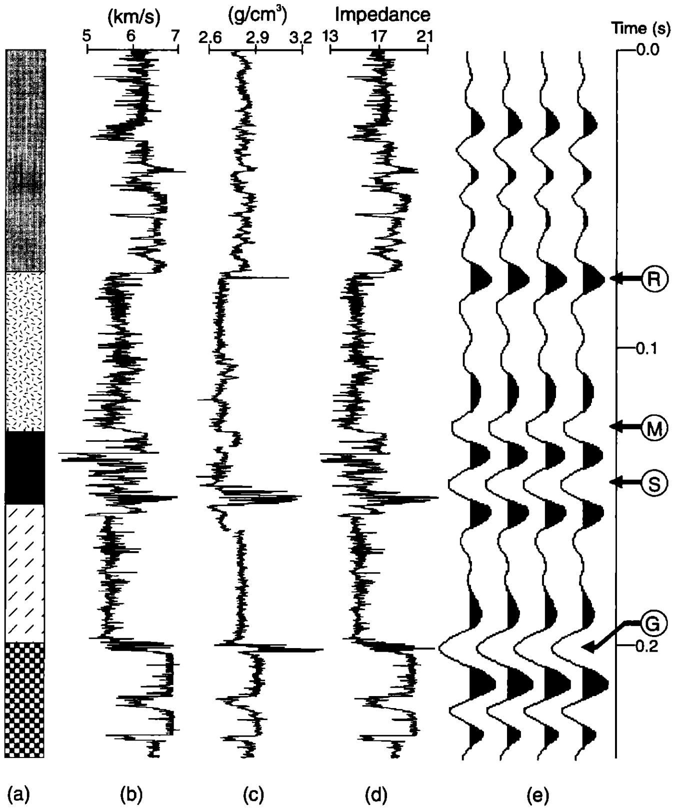

FIG. 5. Lithology (a), velocity (b), density (c), and acoustic impedance (d) logs for BH-4509. Lithology patterns are the same as in Figure 2. Synthetic seismograms (e) were computed from the acoustic impedance log using a 40-Hz Ricker wavelet. G = gabbro contact, M = top of mixed basalt, graphitic argillite, and talc layer, R = North Rhyolite contact, S = top of massive sulfides.

Interpretation

Generalized lithology, velocity and density logs for BH-4509 versus two-way traveltime are plotted in Figure 5. To aid in the interpretation of vertical seismic profile data, a one-dimensional synthetic seismogram (Telford et al., 1990, p. 245) was computed for this borehole using a 40-Hz Ricker wavelet and log-derived acoustic impedance values. Deflections in the synthetic trace correlate with abrupt changes in the acoustic impedance log. The magnitude of each deflection depends not only on the relative magnitude of the corresponding impedance change, but also constructive and destructive interference effects from adjacent layers (e.g., Hurich and Smithson, 1987). The synthetic trace is plotted with a polarity such that positive deflections (shaded in black) correlate with a decrease in acoustic impedance.

The pattern of reflectivity apparent in the synthetic seismogram provides important insight about the seismic expression of the North Rhyolite volcanic complex. The complex is bounded between the North Rhyolite contact (R), represented in the synthetic trace by a positive deflection, and a prominent negative deflection produced by the juxtaposition of low-impedance serpentinized ultramafic rocks and high-impedance gabbros (G). An intervening moderate-impedance layer (M) composed of mixed basalt, graphitic argillite, and talc is underlain by a high-density, pyrite-rich (~35 %) massive sulfide unit (S). Taken together, M and S produce a composite sequence of positive and negative trace deflections, and both units are much thinner or absent in BH-5171.

The most natural way to present and interpret the vertical seismic profile data is in the spatial domain, so that reflectors are displayed in cross sectional format. Repositioning of the reflections was accomplished using the vertical seismic profile CDP transform method (Wyatt and Wyatt, 1984), which maps each data sample to its subsurface location as predicted by two-dimensional ray tracing. The velocity model for ray tracing was determined using P-wave direct arrival time picks. Using this velocity model, a unique position in the subsurface can be assigned to each data point based on its receiver location and travel time. One disadvantage of this approach is that it does not honor true three-dimensional subsurface structure; instead, all data samples are projected into a single plane (Fig. 6, inset). In the two-dimensional image produced by applying this method to the processed radial-component data (Fig. 6), reflections show approximately the correct range of dips (70°–85°). However, the dip of units near the bottom of the section is slightly too shallow, possibly due to lateral velocity variations or anisotropic effects not accounted for in the velocity model.

As discussed previously, coherent reflections that intersect

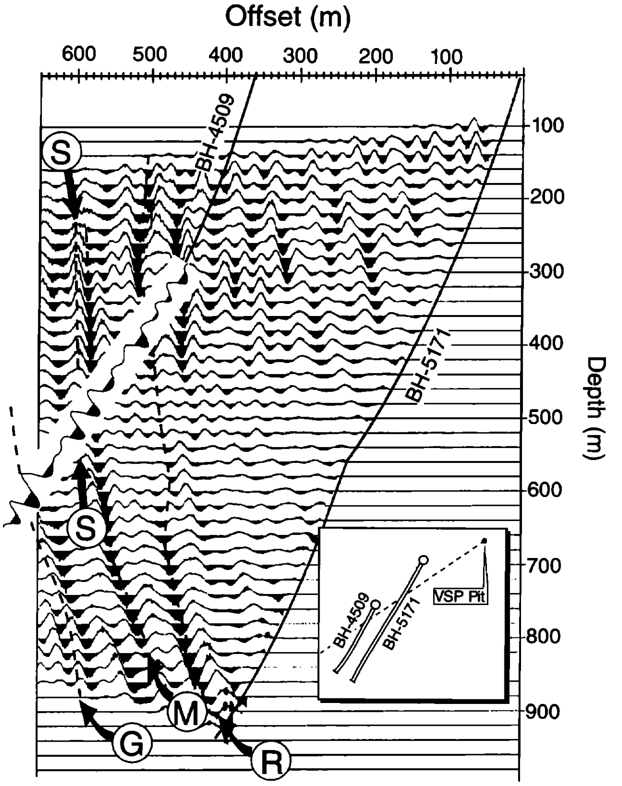

FIG. 6. Radial component (oriented toward the shot) vertical seismic profile (VSP) data transformed from survey coordinates to spatial coordinates, yielding a cross sectional image of the subsurface in the vicinity of the borehole. Depth axis is vertical depth, not wireline depth. Synthetic seismogram from Figure 5 has been plotted in the record section along the projection of BH-4509 (see inset). G = gabbro contact, M = top of mixed basalt, graphitic argillite, and talc layer, R = North Rhyolite contact, S = top of massive sulfides.

the trace of BH-5171 permit the identification of relatively precise stratigraphic ties. For example, reflection R (Fig. 6) intersects the borehole at the position of the North Rhyolite contact and is continuous upward to at least 600 m. Reflections from the North Rhyolite volcanic complex (M, S, and G) occur below and to the southwest of R in Figure 6. Further stratigraphic control is provided by BH-4509, which has been projected into the southwest-northeast-trending plane of the section in Figure 6. The synthetic seismogram computed using the procedure described above has also been plotted along the trace of BH-4509. Correlation of the deflections indicated on the synthetic trace with reflections visible in the transformed vertical seismic profile data provides a basis for interpreting reflections from the North Rhyolite volcanic complex. In particular, the negative reflection labeled S and the adjacent reflection labeled M appear to correspond, respectively, with the massive sulfide deposit and the mixed basalt, graphitic argillite, and talc layer intersected by BH-4509. Neither reflection is continuous to BH-5171, consistent with the observed absence of these units in that borehole. Reflection S builds in amplitude between a 200- and 300-m depth; it contains the largest amplitudes observed in the seismic section. The amplitude and continuity of event S furnishes strong evidence that pyrite-rich massive sulfide lenses which occur in this geologic setting can produce prominent reflections, and are thus detectable by seismic techniques. In this case, the massive sulfide lens detected by the seismic data is approximately 200 m in strike length (horizontal), 350 m in dip length (vertical), averages about 10 m thick, and is approximately 2.45 metric tons.

Conclusions

The case history presented here demonstrates the viability of vertical seismic profiling as a practical method for deep mineral exploration in a crystalline-rock environment characterized by steep dips—a setting in which surface-based seismic techniques may be ineffective. The results of this test survey indicate that small (150–225 g) explosive charges placed in water-filled pits provide sufficient energy to explore to depths of about 1.0 km. By applying an appropriate transformation based on seismic ray tracing, the results of this type of survey can be displayed as cross sectional images. In this case, the vertical seismic profile record section delineates steeply reflections that correlate with stratigraphic contacts in the North Rhyolite volcanic complex. Observed reflectivity in this vertical seismic profile experiment confirms that massive sulfide deposits can produce prominent and readily mappable seismic reflections.

Acknowledgments

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